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published in
Gait and Posture
2014

DOI (link to publisher)
10.1016/j.gaitpost.2014.03.184

Gait & Posture 40 (2014) 166–171

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Test–retest reliability of muscle vibration effects on postural sway

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ARTICLE INFO

Article history:
Received 9 April 2013
Received in revised form 13 March 2014
Accepted 21 March 2014

Keywords:
Postural control
Reliability
Proprioception
Muscle vibration

ABSTRACT

The effect of alterations in the processing of proprioceptive signals, on postural control, has been studied using muscle vibration effects. However, reliability and agreement of muscle vibration have still to be addressed.

This study aimed to assess intra- and interday reliability and agreement of vibration effects of lumbar paraspinal and triceps surae muscles in a non-selected sample of 20 subjects, standing on solid surface and on foam. We used mean position and velocity of Centre of Pressure (CoP), during and after vibration to quantify the effect of muscle vibration. We also calculated the ratio of vibration effects on the lumbar paraspinal and triceps surae muscles (proprioceptive weighting).

Displacement of the CoP during vibration showed good reliability (ICCs > 0.6), and proprioceptive weighting of displacement fair to good reliability (0.52–0.73). Agreement measures were poor, with most CV's ranging between 18% and 36%. Change in CoP velocity appeared not to be reliable. Balance recovery, when based on CoP position and calculated a short period after cessation of vibration, showed good reliability. According to this study, displacement during vibration, proprioceptive weighting and selected recovery variables are the most reliable indicators of the response to muscle vibration.

1. Introduction

Alterations in postural control, as reflected in increased postural sway, have been shown in many disorders, for example in low back pain [1], anterior cruciate ligament ruptures [2], ankle injury [3,4], stroke [5,6], diabetic neuropathy [7] and Parkinson's disease [8]. Optimal postural control not only requires adequate peripheral proprioceptive input, but also the integration of proprioceptive signals from several body parts with signals from the visual and the vestibular system. A commonly used method to test the proprioceptive system in vertical postural control is the sensory organization test (SOT). As part of this test the proprioceptive system is targeted in conditions in which the support surface is rotated with the anterior posterior sway, thus attenuating proprioceptive signals from the ankles. Reports on reliability of these test conditions are diverse, ranging from 0.33 [9] to 0.68 [10] and 0.93 [11] in healthy adults, and from 0.26 to 0.67 in patient populations [9,12].

However, the manipulation used in the SOT attenuates proprioceptive signals from the ankles. Therefore it provides a measure of the ability to compensate for inadequate ankle proprioceptive input, and does not provide insight into the accuracy and the use of proprioceptive signals themselves.

An alternative method to study the proprioceptive system in standing postural control is by stimulating afference from muscle spindles by muscle vibration. Muscle spindles are the principal sensors in proprioception [13], and are sensitive to vibration [14,15]. The signal induced by muscle vibration is perceived as a lengthening of the vibrated muscle [14,15], and during vibration the vertical posture will be adjusted in response to these signals.

For example, subjects with low back pain showed a larger posterior displacement of the centre of pressure (CoP) during Triceps Surae Muscles (TSM) vibration, and a smaller anterior displacement during response to vibration of the Lumbar Paravertebral Musculature (LPM) than healthy controls [16,17].

The ability to reweigh proprioceptive signals from different body regions has been explored by letting subjects stand on an unstable surface, such as a seesaw or a foam pad. In this condition, proprioceptive signals from the TSM are less representative of the

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http://dx.doi.org/10.1016/j.gaitpost.2014.03.184
0966-6362/

actual orientation of the body. Compared to standing on a solid surface, vibration of TSM leads to less displacement of the CoP [18,19], while vibration of the LPM leads to a larger displacement of the CoP [19]. However, subjects with low back pain showed less flexibility in shifting the proprioceptive weighting from the ankle region to the lumbar spine than healthy controls [20].

The use of proprioceptive signals can also be studied by quantifying the time and adequacy of balance recovery after cessation of muscle vibration. Different variables have been used for this purpose. Velocity of the CoP showed a more rapid recovery after cessation of vibration in experts in gymnastics than in other athletes [21], while variability of CoP velocity after vibration was higher in idiopathic scoliosis adolescents than in healthy controls [22]. In elderly subjects, and subjects with low back pain, the time needed to recover the pre-vibration CoP mean position after vibration was longer [16].

Although muscle vibration has been widely used in proprioceptive studies, no consensus exists about which variables to use with which parameters, and no information about reliability and agreement has been reported, while such information is essential for interpreting the results of the studies that use muscle vibration. We therefore conducted a reliability study, to establish reliability and agreement of a wide range of parameters that quantify the effect of muscle vibration of the LPM and of the TSM, on solid and on foam surfaces.

2. Methods

2.1. Subjects

Twenty college students and staff, 11 males, 9 females (age 36 ± 15 yr, weight 81 ± 16 kg, height 179 ± 10 cm) volunteered to participate. Exclusion criteria were known neurological disorders, vestibular impairment or pathologies of the lower extremities. All subjects provided written informed consent and the protocol was approved by the Ethical Committee of Utrecht University Medical Centre.

2.2. Procedure

One complete test procedure consisted of 6 trials. In the first 4 trials, participants stood barefoot on a force plate (Kistler 9286 AA) in a comfortable position (feet shoulder width, arms hanging loosely by the side). Subjects were asked to stand relaxed and immobile, and to face straight ahead with eyes open, but vision was occluded by means of taped safety glasses. Foot position was marked on a transparent to ensure an equal position across trials. Trials 1–4 consisted of a pre-vibration epoch (0–15th second), a vibration epoch (15–30th second), and a post vibration epoch (30–60th second). During the vibration epoch, mechanical vibration was applied to LPM (Trial 1 & 3), and TSM bilaterally (Trial 2 & 4). Two muscle vibrators (Maxon motors Switzerland) were used with a frequency of 70 Hz and amplitude of approximately 0.5 mm. These characteristics have been shown to induce a significant muscle-lengthening illusion [15]. In trials 1 & 3 subjects were standing on a solid surface, in trial 3 & 4 on a foam surface. In Trials 5 and 6, limits of stability were tested on foam and rigid surface, respectively. In these trials, subjects were asked to lean as far as possible forward and backward both during five seconds without bending hips or knees. The tests were performed by three different research assistants who were standing directly behind the participant to prevent actual falls. Trials in which the research assistant touched the participant to prevent him or her from falling were discarded and repeated after a break of at least five minutes. The entire test was performed 4 times, of which 3 tests were performed on Day 1, called habituation test, Test 1 and Test 2, and once on day 2, two weeks later.

2.3. Data reduction and statistical analysis

Force plate data were sampled at 200 samples/s, using Bioware 3.24 software. The data were low-pass filtered using a 2nd order bidirectional Butterworth filter with a cut-off frequency of 3 Hz. All CoP based measurements were calculated using Matlab (version 7.1.1).

Balance control was assessed during (vibration epoch) and following (post-vibration epoch) muscle vibration. During vibration the means of change in COP position (dP) and COP velocity (dV) were calculated. These parameters were also calculated with respect to the each participant's limits of stability.

Proprioceptive weighting was defined as the ratio between the effects of vibration of the LPM and the TSM (absolute TSM/(absolute TSM + absolute LPM)). This ratio gives an indication of the relative reliance on TSM versus LPM afference.

Variables referring to the post-vibration epoch were also calculated relative to the pre-vibration epoch, and relative to the last 5 s during vibration. For a detailed overview of all dependant variables we refer to Table 1.

For calculation of the reliability coefficient, we used the ICC (2, 1), absolute agreement, which accounts for systematic differences between measurements according to the following equation:

$$\frac{\text{MS\_subjects-MS\_error}}{(\text{MS\_subjects} + (k-1) * \text{MS\_error} + k * (\text{MS\_measurements-MS\_error})/n}$$

where MS, mean square, n, number of subjects, k, number of measurements. We calculated the ICC for Test 1 versus Test 2 on day 1 (intraday), and for Test 2 versus Test 3, two weeks later (interday).

The classification of Fleiss [23] was used to interpret our findings, with ICCs < 0.4 representing poor reliability, between 0.4 and 0.75 representing fair to good reliability, and >0.75 representing excellent reliability.

For normally distributed data, we expressed agreement in the Smallest Detectable Difference (SDD). We used the equations for absolute agreement, SEM, square root from (MS_error + MS_measurements); SDD = sqrt(2)*1.96*SEM.

The SDD was expressed as the percentage of the mean in the first test. For heteroscedastic data, the coefficient of variance (CV) and 95% CI was calculated after a log transformation was performed. Data were judged heteroscedastic if the Pearson correlation coefficient between the mean of, and the absolute difference between the first two test tests was >0.3 [24]. The CV was not calculated if a variable contained both negative and positive values.

To detect learning effects, we conducted an repeated measures ANOVA with a polynomial planned comparison for linear trend over the habituation test and the first two tests.

3. Results

A comprehensive overview of intra- and interday reliability and agreement of variables is presented in Tables 2 and 3. For detailed results we refer to the supplemental data. No major deviations from normality were found.

Intra-day ICCs ranging from 0.62 to 0.74 were shown for dP. Interday reliability was, although slightly lower, comparable to intraday reliability (0.59–0.66). Reliability between the habituation trial and Trial 1 was in general lower than intraday and interday reliability (0.37–0.76). A significant learning effect was noted for TSM vibration in both solid ($p = 0.00$) and foam ($p = 0.01$) condition. When repeating the test, dP became smaller. Agreement was poor for dP with CV's up to 36% and SDD's that were in general larger than 100%. Relative to limits of stability, dP was less reliable and showed less agreement (Table 2). In general, ICCs for dV were poor (below 0.4), while no learning effects were found.

Table 1
Variables (2nd column total number of measurements)[a].

Variable		Abbreviation	
Variables during vibration (vibration epoch)			
			Absolute (12)
Displacement	4	d*P*	Mean CoP a/p position during vibration – Mean CoP a/p position pre-vibration. Trial 1 to 4.
Change in velocity	4	d*V*	CoP velocity[b] during vibration/CoP velocity pre-vibration. Trial 1–4.
Proprioceptive weighting displacement	2	Pw d*P*	1. Absolute displacement trial 2/(absolute displacement trial 2 + absolute displacement trial 1) 2. Absolute displacement trial 4/(absolute displacement trial 4 + absolute displacement trial 3)
Proprioceptive weighting change in velocity	2	Pw d*V*	1. Change in velocity trial 2/(change in velocity trial 2 + change in velocity trial 1) 2. Change in velocity trial 4/(change in velocity trial 4 + change in velocity trial 2)
			Relative to limits of stability (14)
Displacement relative to limit of stability	4	d*P* lim rel	1. d*P* during vibration LPM/anterior limit[c] 2. d*P* during vibration TSM/posterior limit[c]
Distance to limit during vibration, absolute	4	d*P* lim abs	1. dPduring vibration LPM – anterior limit[c] 2. d*P* during vibration TSM – posterior limit[c]
Displacement relative to total range of stability	4	d*P* lim tot	d*P*/(distance between anterior and posterior limit)[b]
Proprioceptive weighting displacement, relative	2	Pw d*P* lim rel	1. Absolute d*P* lim rel trial 2/(absolute d*P* lim rel trial 2 + absolute d*P* lim rel trial 1) 2. Absolute d*P* lim rel trial 4/(absolute d*p* lim rel trial 4 + absolute d*P* lim rel trial 3)
Variables expressing balance recovery in the post-vibration epoch			
		Abbreviation	*Related only to the post-vibration epoch (8)*
Half-life 1	2		Time till CoP position reaches half of the final recovery
Time to peak	2		Instant of peak CoP position anterior direction, in first 5 s after vibration (s)
Half-life 2	2		Half-life 1 + time to peak
			Relative to the pre-vibration epoch (40)
Final error	2		Mean CoP a/p position 55–60 s – Mean CoP a/p position pre-vibration
Integral of recovery	2	Avg_pos	Integral of position relative to mean baseline
Velocity	4	ReinV	CoP velocity[b] xth second – yth second/CoP velocity[b] pre-vibration, for $(x-y)$ = (30–35) (35–40)
Velocity Sd	4	ReinVsd	Sd CoP velocity xth second – yth second/Sd CoP velocity pre-vibration, for $(x-y)$ = (30–35; 35–40)
Recovery CoP position absolute	10	$x-y$ abs	Mean CoP a/p position (xth second – yth second) – Mean CoP a/p position pre-vibration, for $(x-y)$ = (30–35; 30–40; 35–40; 40–45; 45–50)
Recovery CoP position, relative to displacement	10	$x-y$ dis	Position recovery absolute/displacement, for $(x-y)$ = (30–35; 30–40; 35–40; 40–45; 45–50)
Maximum overshoot	2		Maximum CoP anterior position 30–35 s – Mean CoP a/p position pre-vibration
Recovery from maximum	6	$x-y$ peak	(Maximum CoP anterior position 30–35 s – Mean CoP a/p position (xth second – yth second)/maxovershoot, for $(x-y)$ = (35–40; 40–45; 45–50)
			Relative to position and velocity during the last 5 s of the vibration epoch (30)
Final error	2		Mean CoP a/p position 55–60 s–Mean CoP a/p position during vibration
Integral of recovery	2	Avg_pos	Integral of position relative to mean baseline
Velocity	4	ReinV	CoP velocity[b] xth second – yth second/CoP velocity[b] during-vibration, for $(x-y)$ = (30–35) (35–40)
Velocity Sd	4	ReinVsd	Sd CoP xth second – yth second/Sd CoP Velocity during vibration, for $(x-y)$ = (30–35; 35–40)
Recovery CoP position absolute	10	$x-y$ abs	Mean CoP a/p position (xth second – yth second) – Mean CoP a/p position during vibration, for $(x-y)$ = (30–35; 30–40; 35–40; 40–45; 45–50)
Maximum overshoot	2		Maximum CoP anterior position 30–35 s[c] – Mean CoP a/p position during vibration
Recovery from maximum	6	$x-y$ peak	Maximum CoP anterior position 30–35 s[c] – Mean CoP a/p position (xth second – yth second)/maxovershoot, for $(x-y)$ = (35–40; 40–45; 45–50)

Variables during vibration calculated for all four trials, vibration of LPM, vibration of TSM, on solid and on a foam surface. Vibration started at 15 s, ended at 30 s.

[a] Number of measurements = number of variables*number of condition*number of time frames. In parenthesis the total number of measurements in a category. Variables of balance recovery calculated only for trials with vibration of TSM, on solid and on a foam surface.

[b] CoP velocity is calculated as the integration of the instantaneous velocities of the CoP over the total observation time.

[c] Limit calculated as the maximal mean a/p CoP position during 1 s, minus the mean CoP position pre-vibration. Limits established in trial 5 and 6.

[d] The epoch immediately after cessation of vibration. Sd, standard deviation.

Table 2
Reliability and agreement of variables in the vibration epoch.

Variable	Intraday reliability and agreement			Interday reliability and agreement			Learning effect
	ICC (95% CI)	SDD (%)	CV (%)	ICC (95% CI)	SDD (%)	CV (%)	*p*-Value intraday
Absolute							
d*P* trial 1	0.68 (0.33–0.86)	192		0.62 (0.2–0.85)			
d*P* trial 2	0.74 (0.44–0.89)	113	28	0.66 (0.25–0.87)	71	36	0.00
d*P* trial 3	0.63 (0.26–0.84)	272		0.61 (0.16–0.84)			
d*P* trial 4	0.62 (0.26–0.84)			0.59 (0.13–0.83)	207		0.01
d*V* trial 6	0.68 (0.32–0.86)		23	0.41 (−0.1 to 0.74)		28	
PW d*P* solid	0.52 (0.12–0.78)	75	22	0.62 (0.19–0.85)		21	0.03
PW d*P* foam	0.73 (0.44–0.89)	87	44	0.41 (−0.13 to 0.76)	66	28	0.04
Relative to the limits of stability							
d*P* lim rel trial 1	0.6 (0.23–0.82)			0.6 (0.17–0.84)			
d*P* lim rel trial 2	0.64 (0.29–0.84)		30	0.5 (0.01–0.79)		42	
d*P* lim rel trial 3	0.54 (0.11–0.79)			0.67 (0.28–0.87)	295		
d*P* lim rel trial 4	0.48 (0.04–0.76)			0.43 (−0.02 to 0.75)			
d*P* lim abs trial 2	0.57 (0.19–0.81)	235		0.48 (−0.03 to 0.78)	117		0.02
d*P* lim abs trial 3	0.46 (0.04–0.75)	138	59	0.54 (0.08–0.81)	80	36	
d*P* lim tot trial 1	0.65 (0.29–0.85)			0.6 (0.18–0.84)			
d*P* lim tot trial 2	0.78 (0.5–0.91)	115	28	0.74 (0.4–0.9)	72	37	0.00
d*P* lim tot trial 3	0.62 (0.24–0.84)	255		0.67 (0.26–0.87)	212		
d*P* lim tot trial 4	0.63 (0.27–0.84)			0.57 (0.12–0.83)			0.00
PW d*P* lim rel solid	0.42 (0.01–0.72)		22	0.47 (−0.03 to 0.78)		22	0.04

Intra and interday reliability and agreement of variables during the vibration epoch.
For abbreviations of variables see Table 1.
Only variables with intra and interday ICC above 0.4 are listed. *p*-Value learning effect only when <0.05.
Trial 1 & 2 on solid surface, trial 3 & 4 on foam surface. Trial 1 & 3 vibration of Lumbar Paraspinal Musculature, trial 2 & 4 vibration of m. Triceps Surea.
Learning effect calculated over habituation trial, first and second trial.

Proprioceptive weighting, expressed as the ratio between d*P*'s, reached intraday ICCs of 0.52 (solid surface) and 0.73 (foam) and interday ICCs of 0.62 (solid surface) and 0.41 (foam). A significant order effect was found for both conditions, on solid surface and on foam. With repeated measurements, reliance on ankle proprioception decreased. Repeated measurements of proprioceptive weighting on solid surface agreed with CV's of 21% and 22%. Reliability of weighting based on d*V* showed ICCs below 0.4.

Only 1 of 8 variables based on CoP in the post vibration epoch, showed fair reliability. Variables that were calculated relative to the pre-vibration epoch showed fair to good reliability for both intra- and interday reliability, when position based and calculated within the first 10 s after cessation of vibration. The highest ICCs for variables reflecting recovery were reached in the foam condition between the 5th and the 10th second after vibration had ceased (interday 0.65; intraday 0.77).

Analogous to the variables calculated relative to the pre-vibration period, the variables expressing recovery relative to the vibration epoch showed the highest ICCs for variables based on CoP mean position within the first 10 s after cessation of vibration. When calculated relative to the last 5 s of the vibration epoch, a larger

Table 3
Reliability and agreement of variables reflecting balance recovery in the post-vibration epoch.

Variable	Intraday reliability and agreement			Interday reliability and agreement			Learning effect
	ICC (95% CI)	SDD (%)	CV (%)	ICC (95% CI)	SDD (%)	CV (%)	*p*-Value intraday
Variables of recovery (8 variables in total)							
Time to peak solid	0.46 (0.03–0.75)		65	0.53 (0.1–0.8)	236	72	
Variables of recovery relative to the pre-vibration epoch (0–15 s) (40 variables in total)							
avg_pos solid	0.4 (−0.02 to 0.71)	613		0.48 (−0.01 to 0.78)			0.003
30–35 abs solid	0.59 (0.2–0.82)			0.5 (0.03–0.79)	2012		
30–35 abs foam	0.45 (−0.01 to 0.75)	362		0.59 (0.15–0.83)	645		
30–40 abs foam	0.62 (0.24–0.84)	239		0.7 (0.34–0.88)	315		
35–40 abs foam	0.77 (0.49–0.91)			0.65 (0.25–0.86)	240		
30–35 dis solid	0.40 (−0.04 to 0.72)			0.66 (0.26–0.86)	1514		
Variables of recovery relative to the vibration epoch (25–30 s) (30 variables in total)							
Final error solid	0.48 (0.06–0.76)	185		0.42 (−0.1 to 0.75)			0.001
avg_pos solid	0.56 (0.13–0.81)	164		0.51 (0.02–0.8)	81		0.001
30–35 abs solid	0.59 (0.22–0.82)		32	0.48 (0.02–0.78)	108	41	0.002
30–40 abs solid	0.62 (0.24–0.84)		100	0.51 (0.03–0.8)	81	115	0.001
30–40 abs foam	0.53 (0.1–0.79)	89	47	0.53 (0.07–0.81)			
35–40 abs solid	0.64 (0.24–0.85)	143		0.53 (0.05–0.81)	78		0.001
35–40 abs foam	0.62 (0.24–0.84)		46	0.4 (−0.04 to 0.73)			
40–45 abs solid	0.58 (0.15–0.82)			0.52 (0.04–0.8)	104		0.001
45–50 abs solid	0.51 (0.07–0.78)	190		0.54 (0.06–0.81)	87		0.001
35–40 peak solid	0.66 (0.31–0.85)	288		0.74 (0.4–0.9)			
35–40 peak foam	0.52 (0.1–0.78)	168		0.46 (0–0.77)	253		
40–45 peak solid	0.51 (0.11–0.77)			0.66 (0.26–0.87)			
45–50 peak solid	0.56 (0.16–0.8)			0.6 (0.16–0.84)			

Intra and interday reliability and agreement of variables reflecting balance recovery in the post-vibration epoch.
For abbreviations of variables see Table 1. All variables calculated for recovery after m. Triceps Surae vibration, one for the solid surface condition, one for the foam surface condition. Only variables with intra and interday ICC above 0.4 are listed.

percentage of all calculated variables reached fair to good intra and interday reliability than when calculated relative to the pre-vibration period.

4. Discussion

Reliability was good for variables based on d*P* during vibration. The fact that intra and interday reliability in d*P* were fairly similar is remarkable and indicates that change in mean position during vibration is a relatively stable phenomenon. These outcomes are promising, bearing in mind that postural control variables in general are subject to significant fluctuations over time. Agreement outcomes, however, were not sufficient to describe differences within individuals over time.

Change in mean position during vibration has been used in numerous studies on proprioception and sensory weighting (e.g. [18,25–27]), but only a few studies included subjects with pathologies. Valkovich et al. [28] vibrated the TSM and compared the magnitude of d*P* between severely affected patients with Parkinson disease, moderately affected patients and healthy controls (all $n = 11$). They found approximately 1.5 times larger d*P* in severely affected patients (4 vs. 2.5 cm) than in both other groups. Brumagne et al. [16] compared 20 healthy subjects with 20 subjects with low back pain. They found a substantial difference between both groups (respectively, 5.9 ± 5.2 cm and 10.4 ± 4.1 cm). The fact that significant between-group differences were established with relatively small groups of subjects in these clinical studies is in line with the reliability (ICC 0.66–0.74) and agreement (SDD 1.6–2 cm) we found in the present study. The d*P* during vibration of the TSM (3–4 cm) in our study fell within the range of the aforementioned studies.

Reliability of the d*V* during TSM vibration does not seem to be sufficient for using this variable in populations without specific pathologies, as indicated by a poor to fair reliability and agreement.

Reliability for proprioceptive weighting based on d*P* on both solid surface and foam was fair to good (ICCs 0.41–0.73). In line with our findings on reliability, Brumagne et al. [20] found significant differences in proprioceptive weighting between subjects with low back pain ($n = 21$) and healthy controls ($n = 24$). In this study, ratios of d*P* during TSM and LPM vibration were comparable with our findings, except for healthy controls when standing on foam, which was 0.46 ± 0.14 compared to 0.69 ± 0.23 in our study. However, bearing in mind that the subjects in our sample were not in- or excluded based on a specific pathology, and consequently the sample also comprised subjects with low back pain, our findings are in line with the results of Brumagne et al. With CV's of 21–22% for solid and 28–44% on foam, this variable could prove useful in clinical settings. Weighting of proprioception expressed as d*V* showed poor to fair reliability, but remarkably good agreement values. This can only be explained by very low between-subject variability. It is therefore possible that this variable discriminates in more heterogeneous populations, such as in subjects with certain pathologies, but another explanation is that this variable is not sensitive to change. We therefore suggest testing the usefulness of this variable in patient populations.

Expressing d*P* relative to the limits of stability partly normalizes vibration effects to individual characteristics, but also introduces a second source of variance. Both effects seem to cancel each other: we did not find an added value to the absolute measurements. The limits of stability are more variable than anthropometrical characteristics; therefore foot length might be an alternative to consider.

Balance recovery has been expressed in velocity and root mean square (RMS) of velocity, to study differences between expert gymnasts and experts in other sports [21], subjects with idiopathic scoliosis and healthy controls [22], and in young versus older people [29]. In all these studies, significant differences were found between groups with small sample sizes (7–9 subjects). In apparent contrast with these findings, we found a poor reliability for these parameters, with ICCs from negative to a maximum of 0.52. It should be noted however that these previous studies used CoP (RMS) velocity after vibration and not the difference between values after and before or during vibration, which could explain this apparent contrast.

Recovery of CoP mean position within 10 s when standing on a foam surface, showed fair to good intra- and interday reliability. Variables that were calculated based on the end of the measurement period after vibration tended to be less reliable. This was probably caused by the substantial part of the subjects that achieved their original mean position before the end of the 30 s period, thus making variation between subjects small and meaningless. Agreement of recovery variables was too low for these variables to be used at the individual level.

When using the CoP mean position during vibration as reference, more recovery variables reached fair to good reliability than when using the pre-vibration period as reference. Moreover, individuals return to a position after cessation of vibration, starting from the perturbed position. The larger the perturbation, the more recovery is necessary. It can therefore be argued that referencing to the CoP mean position during vibration provides a better measure of recovery.

As a result of vibration cessation, subjects showed an abrupt forward movement to a peak anterior position. We also expressed recovery as the distance between the maximum anterior CoP position that occurred in the response to stopping the vibration ("peak") and the mean CoP position during the last 5 s of vibration. This variable showed the highest intra and inter-day ICCs of all tested variables on solid surface, but reliability on foam surface was only fair.

The protocol we used was designed to be used in a large cohort. This provides a number of potential threats to the validity of this study. One of those threats is the fixed order used for the trials. As a consequence, vibration applied when standing on foam always followed vibration when standing on a solid surface. Although this could result in higher ICCs for trials on foam through a habituation effect, we have reasons to assume that this phenomenon did not significantly influence our findings. There was a period of at least two minutes between two trials on the same muscle group. Moreover, reliability on foam was not structurally larger than on a solid surface.

We also noticed that less experienced experimenters tended to place the vibrators too low on the lumbar spine, thereby reducing the impact of vibration on muscular tissue. A thorough training of the experimenters could therefore increase reliability and agreement of the variables measured. In addition to the training, a buckle transducer in the belt could be used to standardize the tension in the Velcro straps and hence the contact force between vibrators and the underlying tissue. Reliability and agreement could further be improved by using mean data from more than 1 trial. Reliability as reported here refers to reliability after one habituation trial, which we regard as necessary in view of the strong learning effect between this trial and Trial 1.d*P* and proprioceptive weighting of d*P* showed sufficient reliability to be useful in studying the processing of proprioceptive signals. Expressing d*P* relative to limit of stability did not improve reliability or agreement. d*V* appeared not reliable in this study, but agreement measures of proprioceptive weighting expressed in d*V* showed good agreement without any learning effect, which suggests that further testing of this variable is warranted. Recovery of position over a short period after cessation of vibration is more reliable than over longer periods. Balance recovery is preferably calculated relative to the period during vibration.

Acknowledgement

There were no external sources of support.

Conflict of interest

None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2014.03.184.

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